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*Submitted to:*

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FORM 836 (10/96)

# The Evolution of North-South Aligned Auroral Forms into Auroral Torch Structures: The Generation of Omega Bands and Ps6 Pulsations via Flow Bursts

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**Abstract.** Although auroral torch structures and omega bands have been observed and studied for decades, a satisfactory understanding of how they form has yet to be achieved. Using global auroral imager data, we show conclusively that the equatorward moving north–south (NS) aligned auroral forms that are ejected episodically from the poleward boundary can evolve directly into torch structures which contribute to a well-defined omega-band form. And that as a consequence, omega bands can be produced as a direct result of earthward-directed bursty bulk flows (BBFs).

## 1. Introduction

*Torches and Omega Bands*

Omega bands are large-scale, discrete auroral folds that develop in the morning sector during substorms (*Akasofu* [1974]; *Saito* [1978]; *Rostoker and Barichello* [1980]) or following substorm intensifications (e.g. *Pellinen et al.* [1992]) and during SMC ('Steady Magnetospheric Convection') or convection bay like intervals (e.g. *Solovyev* et al. [1999]). They typically occur at the poleward edge of the diffuse auroral region but are embedded in the most equatorward component of the so-called double oval configuration that also develops in the later phases of an auroral substorm or during SMC-like intervals. They are characterized by a series of (roughly) north–south aligned protrusions which extend poleward toward the higher latitude component of the double oval and are azimuthally separated by dark regions. The poleward protrusions or "tongues" of luminosity were originally referred to as "auroral torches" by *Akasofu and Kimball* [1964]. When more than one such torch exists, the auroral pattern resembles a series or "band" of inverted Greek letter $\Omega$'s with the concave portion of each $\Omega$ pointing poleward.

Omega bands vary in azimuthal size between a few hundred kilometers to several thousand kilometers and are typically observed to drift eastward at speeds between $0.4$- $2$ km/s – although individual torch-like structures have occasionally been observed to drift westward as well. In addition, it has been shown that omega bands are associated with long-period Ps6 magnetic pulsations with a 4-40 minute period (a special substorm-associated subclass of long-period Pi3 irregular magnetic pulsations) (e.g. *Saito* [1978]; *Kawasaki and Rostoker* [1979]; *Opgenoorth et al.* [1983]; *Buchert et al.* [1988]) and that each packet of Ps6 pulsations corresponds on a one-to-one basis with the occurrence of a low-latitude Pi2 pulsation (e.g. *Saito* [1978]).

*Oguti et al.* [1981] has also determined that the central regions of the bright poleward protrusions or torches are activity centers for pulsating auroras during magnetically active periods.

The equivalent ionospheric current systems derived from ground magnetometer and radar measurements shows that omega bands are associated with a series of eastward-drifting pairs of upward and downward field aligned current (FAC). The western edges of the luminous torches are associated with regions of upward FAC while the westernmost edge of the dark voids between the torches are associated with downward FAC (*Wild et al.* [2000]).

Although omega bands have been observed for decades, a satisfactory explanation of how they are formed is still lacking (*Wild et al.* [2000]). *Yamamoto et al.* [1997] proposed that they are created as a consequence of an interchange instability in the diffuse auroral region, but as *Wild et al.* [2000] point out, the structure of the observed FACs is inconsistent with this model. On the other hand, *Wild et al.* [2000] conclude that their observations are consistent with the omega bands forming as a result of a Kelvin-Helmholtz type instability near the poleward boundary of the auroral oval of the sort invoked by *Hallinan* [1976] in order to explain auroral spirals, folds and curls. However, as we have discussed above, the omega bands do not form at the poleward boundary of the auroral oval. Instead, they typically form in the equatorward component of an active double oval type configuration – well equatorward of the poleward boundary.

*PBIs and North-South Aligned Auroral Forms*

Substorms and SMCs can be viewed as an ensemble of a series of more elemental episodes of activity that recur at intervals of 5-15 minutes (or more). These events are typically associated with an activation of the most poleward arc system (called Poleward Boundary Intensifications or PBIs) followed by the equatorward ejection of North-South (NS) aligned auroral forms from the poleward arc into the bulge (e.g. *Rostoker et al.* [1987]; *Nakamura et al.* [1993]; *Henderson et al.* [1994]; *Henderson et al.* [1998]; *Lyons* [2000]). The activations of the poleward arc system typically include an intensification (sometimes observed to travel eastward along the arc system) and/or the creation of new arcs at the poleward edge. In the western part of the bulge, the equatorward moving forms have an east-west or northeast-southwest alignment, while farther to the east the structures are more clearly north–south aligned. Once in the bulge (or in the gap between the equatorward and poleward components of a double oval configuration) the auroral forms below the surge drift in a clockwise sense (as viewed along the B-field direction). And in the post-midnight side of the bulge, the NS forms generally drift eastward.

After the NS forms are injected into the bulge, they propagate toward the equatorward boundary where they become broader and more diffuse in appearance and resemble torch-like structures. The remnants of this activity produce a wavy, structured appearance to the equatorward component of the double oval configuration. And as *Nakamura et al.* [1993] have shown, the NS aligned auroras typically evolve into diffuse pulsating auroral forms as they drift eastward into the morning sector. In addition *Solovyev* et al. [1998] have shown that in the evening to premidnight sector, a quasi-periodic sequence of north–south aligned auroral forms can excite Ps6 magnetic pulsations there.

These more elemental episodic events are characteristic of both substorms and SMCs (and storms since they are merely an ensemble of substorms and SMC-like behavior) and are probably the auroral signatures of: the "micro-substorms" observed by *Sergeev* [1974] and *Yahnin et al.* [1983]; the "substorm intensifications" described by *Rostoker et al.* [1980]; and the "multiple onset substorms" described by *Pytte et al.* [1976]. *Rostoker et al.* [1987] originally interpreted substorm-related north–south aligned auroral forms as "the projection on the ionosphere of the drift paths of [localized blobs of] energetic electrons as they drift from the magnetotail into the more dipolar inner magnetosphere", and *Liu and Rostoker* [1993] proposed a model in which these "plasma blobs" are injected into the central plasma sheet from the adjacent low latitude boundary layer.

In recent years, it has been demonstrated that the PBI/NS auroral events are very likely the ionospheric manifestation of Bursty Bulk Flows (BBFs) in the tail (*Henderson et al.* [1998]; *Sergeev et al.* [1999]; *Zesta et al.* [2000]). Thus, the elemental mode of earthward transport in the tail (BBFs) has been plausibly connected with the elemental mode

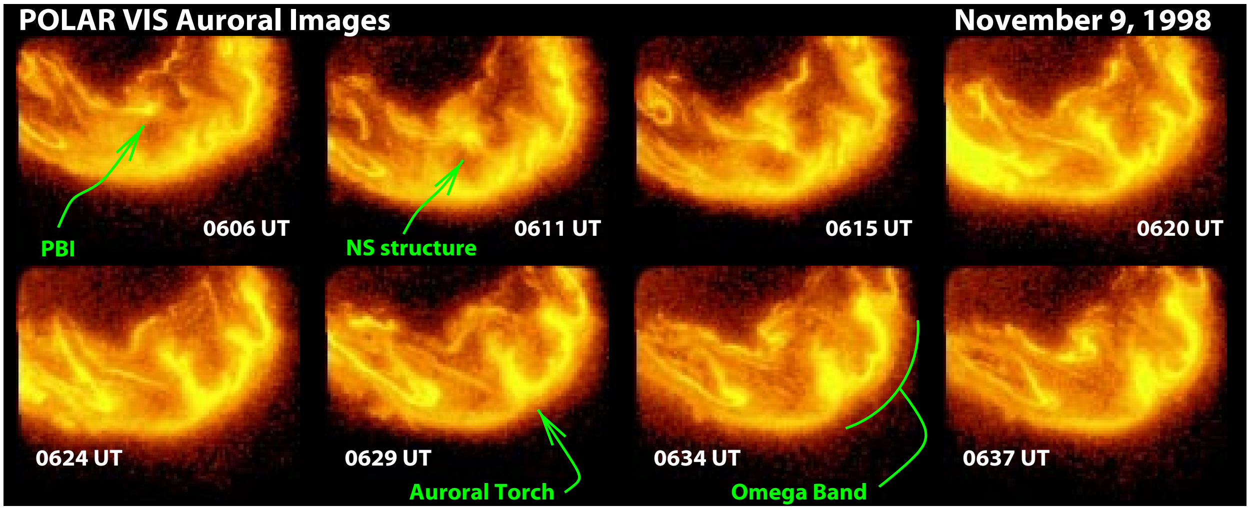


**Figure 1.** Images of the Earth's northern auroral distribution acquired by the Polar VIS auroral imager on November 9, 1998. This sequence of images shows a poleward boundary intensification followed by the equatorward ejection of a north–south aligned auroral structure and subsequent formation of a torch and omega-band undulation. This is one of a series of similar events.

of auroral activity in the ionosphere (the PBI/NS events). Note that this interpretation is not inconsistent with that of *Rostoker et al.* [1987] or *Liu and Rostoker* [1993] since BBFs may be generated in more than one way (e.g. see *Chen and Wolf* [1993]).

From the foregoing introduction, it is clear that there is a remarkable similarity between the remnants of PBI/NS events and auroral torch structures. Thus, it seems likely that the two features are either the same thing or are at least intimately related to one another. The possibility of a connection between the two types of features has also been suggested recently by *Solovyev* et al. [1999]. The purpose of this study is to show conclusively that PBI/NS events can indeed evolve directly into torch structures which contribute to a well-defined omega-band form. And that as a consequence, omega bands and Ps6 pulsations are likely produced as a direct result of earthward-directed BBFs.

## 2. Observations

On November 9 1998, the auroral distribution displayed a long-lived, active double-oval type configuration. The auroral dynamics were characterized by repetitive episodes of poleward boundary intensifications and equatorward ejection of north–south aligned auroral forms, and by the presence of a well developed and intense morning sector omega band structure. Thus, the auroral configuration was very similar to that of a very long-lived substorm recovery phase or SMC-like interval.

In Figure 1 we present a sequence of images acquired with the Polar VIS auroral imager during this time period to illustrate how the ejection of a single north–south aligned auroral form from the poleward component of the double oval was related to the formation of the omega bands residing on the equatorward part of the double oval configuration. As shown, a poleward boundary intensification (PBI) was observed at 0606 UT followed by the ejection of an equatorward moving north–south (NS) aligned auroral structure between 0611–0620 UT. By 0629 UT, the north–south aligned form has evolved into a classic torch-like structure at the western edge of a well developed omega band structure. When the images are animated the omega bands are clearly seen to drift eastward and the evolution of the NS form into the torch structure is very clear and dramatic. Several other episodes of PBI/NS auroral activity occurred throughout this time period and each behaved in a similar manner.

In Figure 2, we present another sequence of images acquired a few hours later (between 0848 and 0933 UT) illustrating the formation of an additional torch and omega band structure. The first 8 images taken between 0848 and 0909 UT clearly show a PBI/NS event evolving into an auroral torch which adds an Ω to the omega band structure on the equatorward component of the double-oval auroral distribution (see the green annotation in Figure 2). This

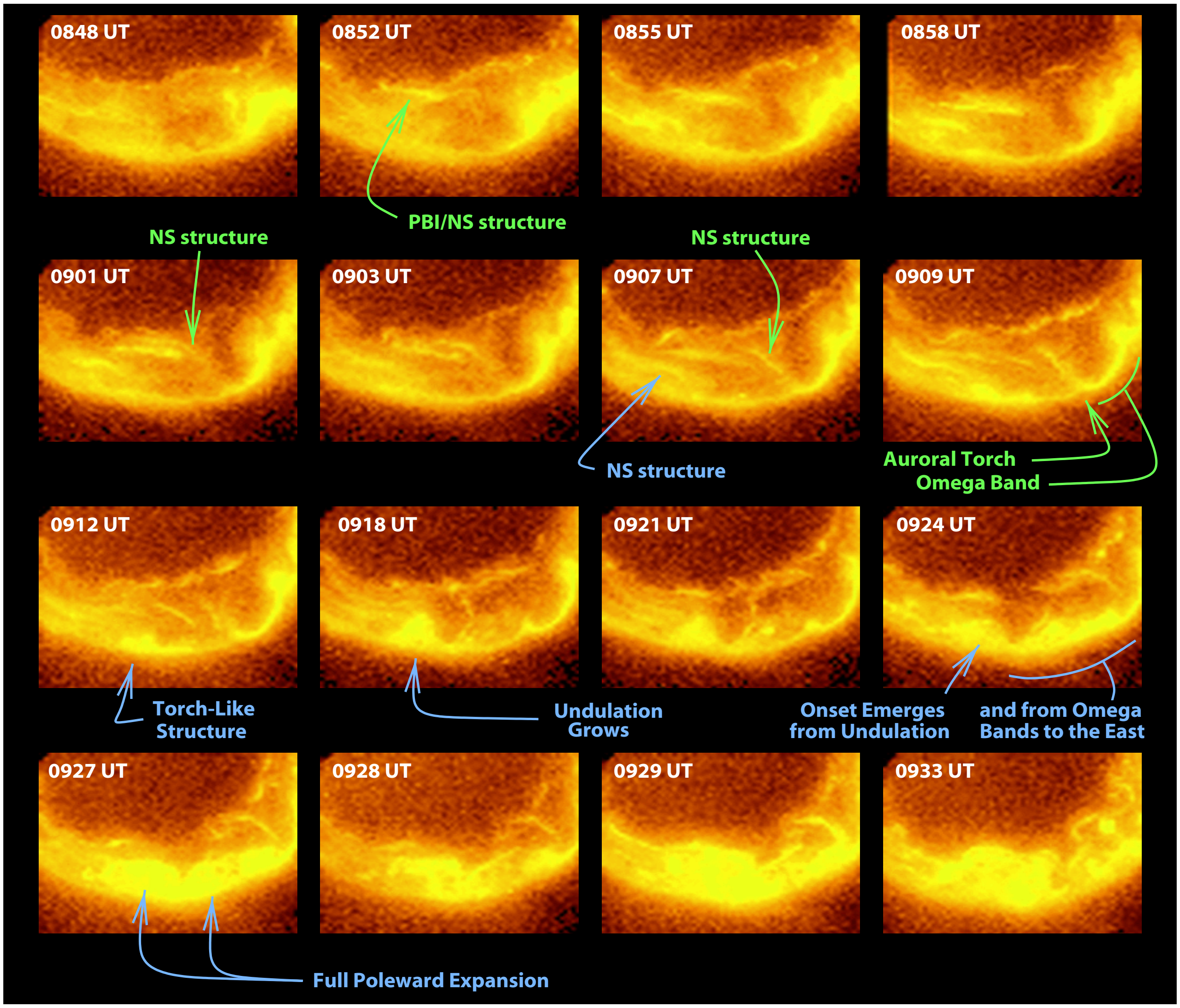


**Figure 2.** Images of the Earth's northern auroral distribution acquired by the Polar VIS auroral imager on November 9, 1998. This sequence of images shows north-south aligned auroral forms evolving into torch-like structures and omega bands. The westernmost undulation grows and becomes the site of an embedded onset.

behavior is very similar to that shown in Figure 1, except that the NS structure is considerably narrower in this example.

Another extremely interesting feature shown in Figure 2 is the occurrence of an "embedded" substorm onset at 0923 UT. Between 0907 and 0912 UT, a broad torch-like undulation on the equatorward component in the premidnight sector begins to form (probably as a result of the equatorward-moving northwest-southeast aligned auroral structure poleward of it). By 0918 UT, this undulation has grown substantially. And at 0923-0924 UT, an embedded auroral onset emerges from it and from the omega band forms farther to the east. This behavior demonstrates quite clearly that new auroral onsets can be intimately related to pre-existing omega band structures at the equatorward edge of a double oval distribution. This is consistent with recent studies by *Connors et al.* [2002] and *Wild et al.* [2000] in which onsets were reported in association with pre-existing omega band forms and/or Ps6 pulsations. A more detailed analysis of this "embedded" onset will be published in a separate paper.

## 3. Discussion and Conclusions

We have shown that PBI/NS events can evolve directly into torches and omega bands. This in addition to studies which have reported a one-to-one correlation between PBI/NS events and BBFs in the tail (e.g. *Zesta et al.* [2000]) and correlations between BBFs and Pi2 pulsations (e.g. *Kepko et al.* [2001]), provide extremely compelling evidence that torches and omega bands can be created as a direct result of earthward-directed flow bursts.

We propose a scenario in which the flow bursts brake as they approach the Earth (e.g. see *Shiokawa et al.* [1998] and *Birn et al.* [1999]) and produce narrow "current wedgelets" comprised of longitudinally paired FACs (downward FAC to the east of an upward FAC in the northern hemisphere) that close through the ionosphere. The FACs expected from this picture are consistent with those that are known to exist in torch/omega band structures (e.g. *Wild et al.* [2000]). And, consistent with the Flow Cyclotron Maser (FCM) model of *Demekhov and Trakhtengerts* [1994], the associated injection and subsequent drift of a fresh population of energetic particles could be responsible for the occurrence of the observed auroral pulsations in torch (and patch-like) structures.

In order to generate a quasi-regular sequence of torch structures (i.e. an omega band) and associated Ps6 magnetic pulsations, three different variations on the foregoing scenario can be envisioned. First, such a sequence can be produced by a quasi-periodic sequence of earthward-directed BBFs. (Each resulting torch will be carried into the morning sector as a result of drifts in the inner magnetosphere.) Second, multiple BBFs can be launched earthward at the same time but at different longitudes. And third, a single BBF can excite the growth of azimuthal wave modes in the near-earth region which would produce additional omega-band like undulations.

In the first variation above, a quasi-periodic sequence of flow bursts and Pi2 pulsations should be observed as the omega band is manufactured in a piecewise sense, while the other two variations would produce an omega band and associated Ps6 waveforms that were initiated by a single (perhaps complex) burst of Pi2 pulsations. We suspect that all three of these mechanisms can operate to produce omega bands and Ps6 disturbances, but further analysis is required to confirm this hypothesis and to elucidate the relative importance of each.

Although more analysis is required, this new paradigm for omega band generation shows how the tail can be coupled to the inner region via flow bursts and appears to successfully explain many if not all of the observed characteristics of torches and omega bands that have been reported over the years including: their relationship to substorm phase; the observed irregular wavelengths; and the observed snake-like undulations of the westward substorm electrojet.

In addition – although implicit in the foregoing discussion – we should point out that the scenario proposed here may also imply a significant shift in thinking for the role of the flow-braking mechanism in substorms. In this new paradigm we see that rather than producing the poleward/tailward movement of the envelope of activity in the ionosphere/magnetosphere, flow bursts and flow braking instead mediate the coupling between the reconnection site in the tail and the near-Earth magnetosphere – that is they couple the poleward component of a double oval configuration with it's equatorward component. New "embedded onsets" can be preceded by or perhaps even triggered by flow bursts, but the subsequent expansion of the large-scale envelope of activity is not likely to be a sole consequence of flow braking (or else each and every torch structure that forms from a PBI/NS event would result in an auroral onset – and they don't).

As a final comment, we would also like to point out that the close association between the embedded auroral onset (at 0923 UT) and the growth of omega band undulations on the equatorward component of the double oval is an extremely important observation that may shed considerable light on the physical processes responsible for the onset (at least in this case). Perhaps these observations are consistent with a type of ballooning mode instability that becomes (spatially) more unstable as undulations are set up farther toward the pre-midnight sector – which would explain why many of these types of onsets appear to occur near the western edge of omega band forms as they penetrate into the pre-midnight sector. We will persue these ideas in greater detail in a subsequent study.

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